Conceptual Design Report of Vacuum pumping system for Main Injector

Shuxiu Zhang
Fermi National Accelerator Laboratory

December 30, 1991

Contents

1 Introduction

The construction of the Main Injector will be one of several important projects to upgrade the Fermilab HEP program during the pre-SSC era.

The decision, made early in the conceptual design, to reuse 30 l/s VacIon sputter ion pumps for the Main Injector was basically one of economics. But the mean pressure of 1×10^{-8} Torr in the new vacuum system, instead of 1×10^{-7} Torr in the Main Ring, requires the application of ultra high vacuum standards and practices.

The required vacuum pumping system can be produced by proper choice of materials, construction, seals, pumping system design, surface treatment and pump down techniques. The key point in the design and construction of the vacuum system for the Main Injector is surface cleaning technology in order to establish and protect very low outgassing rates of materials. A number of surface treatment techniques, such as chemical cleaning, vacuum fire, glow discharge cleaning and *in situ* bake out, have been developed in various laboratories, are all typical for ultra high vacuum technology or for accelerators and storage rings. The aim of this study is to investigate and draw up Fermilab procedures which will be applicable to the Main Injector.

2 Original design

The following contents are extracted from "Conceptual Design Report: Main Injector (April 1990)":

The vacuum system for the Main Injector will be similar to the Main Ring system. Each dipole magnet chamber will have a port for 30 l/s Troide VacIon pump and straight sections will have a port approximately every six meters for the same type of pump. Ion pumps and their power supplies from the Main Ring will be reused.

The design goal of vacuum is an average pressure of 1×10^{-8} Torr. With this pressure storage times of minutes at 8.9 Gev/c will be available for studies.

Gate valves will be used to divided the Main Injector sectors. There will be a gate valve at the end of each straight section with appropriate interlocks. There will be a total of 32 gate valves in the system.

The beam lines will use the same ion pumps as the Main Ring, spaced approximately every 12 meters.

Vacuum pressure during pump down will be monitored by a combination of thermocouple and cold cathode gauges; high vacuum will be monitored by the current readout of each ion pump.

Vacuum pump down will be done using portable turbo-molecular units that can be wheeled to any area being worked on. Ten units are provided.

3 Design requirements

The design of the vacuum system for the Main Injector must satisfy the following requirements:

1. A basic vacuum requirement for a proton accelerator depends on the degree of beam degradation which can be tolerated during the passage through the machine, on the intensity loss by Coulomb and nuclear scattering of the residual gas, and on the energy losses through molecular excitations. It also depends directly on the product of residual gas pressure and particle path length. In practice, the vacuum of high energy particle accelerators can be affected in a number of ways by the introduction of the circulating beam. The vacuum system of the Main Injector must provide a dynamic pressure of 1×10^{-8}Torr on the beam orbit. Corresponding to a static vacuum without beam, a pressure of less than 5×10^{-9} Torr causing only normal thermal outgassing of the chamber walls should be required.

2. Pump-down time, pumping from atmosphere to operating pressure, is another important requirement for a vacuum system. The pump-down time for the Main Injector should be less than 48 hours.

3. The system must be capable of quick recovery after sections are vented and opened up for alteration or accident during routine maintenance.

4. In a large machine, reliability of components is essential. Because of thousands of pairs of flanges and feedthroughs on the Main Injector, each component must be highly reliable.

5. The system should require little operator intervention for normal operation and a minimum service in the tunnel. The elements of the system should be simple for maintenance.

6. The expected high level of radiation imposes onto the special

requirement connected with the safety of the servicing personnel as well as with the changes in the properties of the constructional materials under the influeunce of radiation.

7. The vacuum system of the Main Injector should be compatible with the magnet, acceleration and other systems.

4 Brief description of the vacuum system

It is an ultra high vacuum system. The ring vacuum chamber of the Main Injector consists of high conductance limited tubular beam pipes with a length of about 3.3 km and five new beam lines with a total length of about 1.5 km which are required to integrate the Main Injector into the existing Booster, Antiproton source, Tevatron and Switchyard. The normal Main Injector machine periods, housing the main bending and focussing magnets, will cover about 70 % of the ring circumference. The remaining part will be occupied by eight straight sections, six of 'long straight' type and two 'R.F.' type, containing the equipments for the beam injection, acceleration and extraction. The whole ring system will be divided by all metal gate valves into 16 sections. Each section will be fully independent from vacuum production.

The vacuum pump layout in the normal periods will be mainly determined by the magnet lattice. As main pumping equipments, more than five hundred VacIon 30 l/s sputter ion pumps will be distributed along the beam tunnel, and conveniently placed at each magnet position port at about 6 m spacing to ensure the low pressure pumping. In the straight sections which will contain the special equipments and their associated important gas loads, some 100 and 200 l/s sputter ion pumps will be installed for an additional pumping. The beam lines will use the same 30 l/s VacIon sputter ion pumps placed about every 12 meters. The rough pumping will be obtained by portable turbo-molecular pump units.

Each sector of the vacuum system will have one vacuum measuring array including a Pirani, a Penning and a B-A gauge allowing pressure measurements from atmospheric pressure down to 10^{-10} Torr. A number of residual gas analyzers will be used for monitoring vacuum behaviour of the system.

4 Brief description of the vacuum system

It is an ultra high vacuum system. The ring vacuum chamber of the Main Injector consists of high conductance limited tubular beam pipes with a length of about 3.3 km and five new beam lines with a total length of about 1.5 km which are required to integrate the Main Injector into the existing Booster, Antiproton source, Tevatron and Switchyard. The normal Main Injector machine periods, housing the main bending and focussing magnets, will cover about 70 % of the ring circumference. The remaining part will be occupied by eight straight sections, six of 'long straight' type and two 'R.F.' type, containing the equipments for the beam injection, acceleration and extraction. The whole ring system will be divided by all metal gate valves into 16 sections. Each section will be fully independent from vacuum production.

The vacuum pump layout in the normal periods will be mainly determined by the magnet lattice. As main pumping equipments, more than five hundred VacIon 30 l/s sputter ion pumps will be distributed along the beam tunnel, and conveniently placed at each magnet position port at about 6 m spacing to ensure the low pressure pumping. In the straight sections which will contain the special equipments and their associated important gas loads, some 100 and 200 l/s sputter ion pumps will be installed for an additional pumping. The beam lines will use the same 30 l/s VacIon sputter ion pumps placed about every 12 meters. The rough pumping will be obtained by portable turbo-molecular pump units.

Each sector of the vacuum system will have one vacuum measuring array including a Pirani, a Penning and a B-A gauge allowing pressure measurements from atmospheric pressure down to 10^{-10} Torr. A number of residual gas analyzers will be used for monitoring vacuum behaviour of the system.

5 Pressure distribution in beam pipes and required outgassing rate of materials

It is supposed that, in the course of the design of the vacuum system for the Main Injector, there are some considerations for the pressure distribution in the ring. The pressure will be monitored at several points. And vacuum gauges will be placed near ion pumps so that the actual mean pressure will be as a whole higher than the monitored pressure. Since pressure dependent lifetime is determined by the mean pressure along the entire ring, a calculation of a detailed pressure distribution in the ring is needed.

Pressure distributions along the beam path in tubular vacuum chamber were calculated based on the pumping system, in which a number of pumps and a distance between two pumps were given. In this calculation, it may be assumed that the outgassing rate of materials is well-distributed along the pipe. Consider three typical pieces of the beam pipe with a length of about 6 m: a dipole magnet, a quadrupole magnet and a straight section(ϕ150mm) vacuum chamber, the main parameters are listed in the following table.

chamber type	dipole	quadrupole	straight section
shape of the cross section	quasi-elliptical	quasi-rhombic	circular
outside perimeter cm	28.89	32.36	47.1
cross section area cm^2	50.6	70.3	176
outgassing area m^2	1.8	1.94	2.8
volume l	30.3	42	106
specific conductance l/s-m	51	90	408
mean pressure Torr	1×10^{-8}	1×10^{-8}	1×10^{-8}
monitored pressure Torr	8.0×10^{-9}	8.7×10^{-9}	9.7×10^{-9}
pressure drop Torr	3.0×10^{-9}	2.1×10^{-9}	0.5×10^{-9}

Fig.1 shows pressure distributions in the dipole(dashed line), the quadrupole(dot-dashed line) and the straight section(solid line) beam pipe with the same mean pressure of 1×10^{-8} Torr(dotted line). For the vacuum design goal, the mean pressure of 5×10^{-9} Torr in the ring should be required at a static status. That means that an average outgassing rate of materials less than 5×10^{-12} Torr

$l/s\text{-}cm^2$ should be targeted in order to satisfy vacuum requirements for the Main Injector. Fig.2 shows the pressure distributions in the beam pipes with the average outgassing rates of 5×10^{-12} Torr l/s-cm^2. Because of larger outgassing surface area, the pressure in the circular pipe(solid line) will be higher than the others.

Fig.1 Pressure distributions in beam pipes

with the mean pressure of 1×10^{-8} Torr

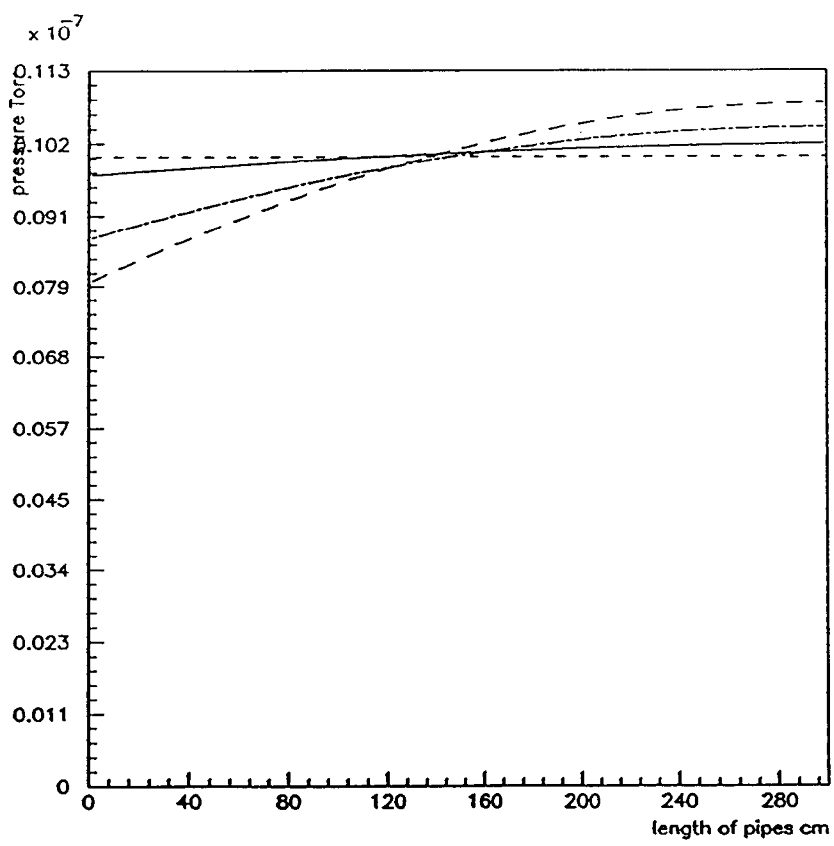
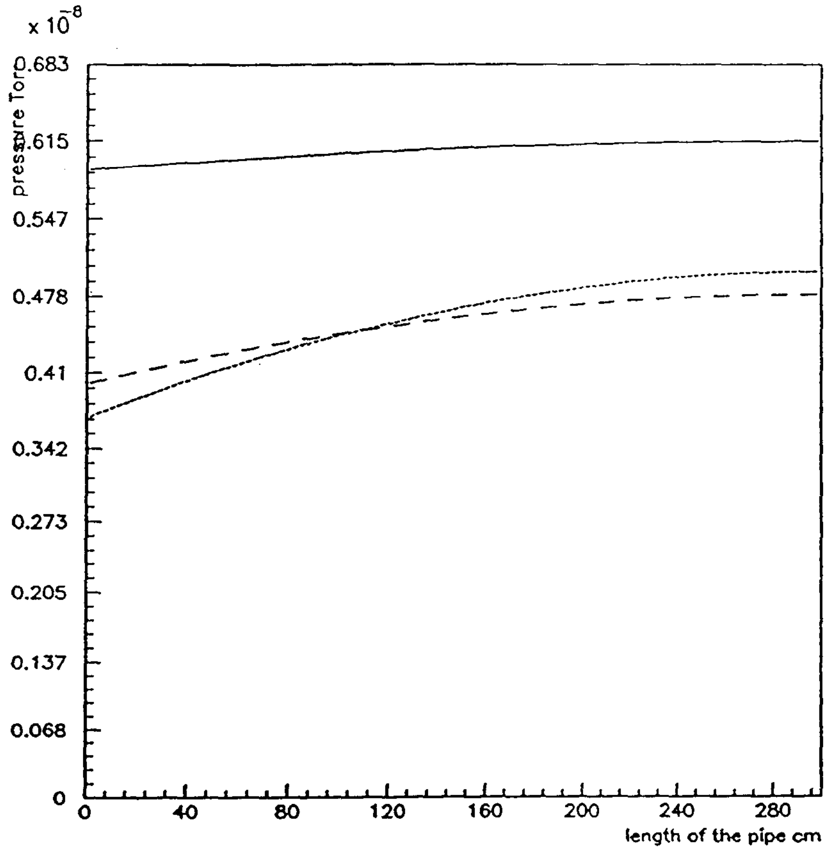


Fig.2 Pressure distributions in beam pipes

with the average outgassing rate of 5×10^{-12} Torr l/s cm^2



6 Surface treatment of materials

6.1 Introduction

In order to enable a pressure of less than 1×10^{-8} Torr to be obtained in beam pipes, an outgassing rate of materials should be as low as $\sim 10^{-12}$ Torr l/s cm^2. In ultra high vacuum technology a myriad of surface treatment techniques which have been developed in various laboratories can be classified as follows:

1. Machine work: milling, grinding, polish and vacuum blast.
2. Chemical cleaning: chemical solution, detergent, pickling and alkaline cleaning, electropolishing and reactive gas cleaning.
3. Heat treatment: bake out, vacuum fire.
4. Ion and electron bombardment: glow discharge cleaning and electron induced desorption, etc.

6.2 Typical technology for accelerators and storage rings

1. Chemical cleaning

This is a basic method for the vauum system. It consists mainly of the following functions: degreasing, chemical etching or polishing, surface passivation and final rinse and drying. A 'Standard' chemical cleaning procedure developed by CERN and BNL has been widely used in laboratories. [1]

2. Electropolishing

An electropolished surface may be considered to be very good due to the removal of the thick oxide layers from stainless steel surfaces. When a metal surface is electropolished, electrical current and chemical activity work together to dissolve metal in a carefully controlled manner. By removing ridges and burrs first, electropolishing actually levels the surface of the part. This smooth surface is also brightened due to the cleaning action of the electropolish-

[1] Surface conditioning of vacuum system, p.93, American Institute of Physics, 1990

ing process. Nagamitsu Yoshimaru has reported that an outgassing characteristic of 10^{-14}Torr l/s cm^2 has been obtained for electropolished SUS 304 plates. [2]

3. Bake out

Bake out is a traditonal way to obtain ultra high vacuum widely used in laboratories. The bake out temperature depends on the required working pressure of the system. The system may be equipped with heating tapes or jackets, or/and Joule heating induced by a direct circulation of currents in beam pipes.

4. Vacuum fire

High temperature vacuum fire is known to be a bulk degassing treatment commonly used for the accelerators. The outgassing of hydrogen in stainless steel is the diffusion from the bulk instead of the desorption from the surface. The amount of outgassing is proportional to the hydrogen content in the metal, which is greatly reduced after vacuum firing. According to a common practice at CERN, most of vacuum chambers and components have been vacuum fired at 950°C for two hours at a pressure of 10^{-5} Torr. In the Accumulator Ring at Fermilab, all stainless steel parts were vacuum fired at 900°C after forming and pre-assembly. During pump-down, using ion pumps only without baking out the system, a pressure of less than 1×10^{-8} Torr was achieved within a few days pumping. [3]

5. Glow discharge cleaning

It has been shown by means of Auger electron spectrometer that the normal solvent cleaning is unable to provide a contaminant free stainless steel surface. The major impurity on the surface is carbon. Glow discharge cleaning can readily remove CO and produce nearly atomically clean surfaces. This not only minimizes the ion-induced

[2] Nagamitsu Yoshimaru, Outgassing characteristics and microstructure of an electropolished stainless steel surface, J Vac. Sci. Technol. A(2), Mar./Apr. 1990

[3] F.E.Mills, et al., Fermilab Accumulator ring ultra high vacuum system, J. Vac. Sci. Technol. A4(3), 1986

molecular desorption and hence reduces pressure, but also in particular improves the vacuum stability in accelerators and storage rings.

6. *In situ* treatment

The vacuum requirement of the Main Injector is very critical in the area of vacuum techniques. Cleaned components and devices have to expose to air during the assembling and installation. After atmospheric exposure, even if done under well controlled venting with dry nitrogen, the desorption yield increases to almost its original value. It is unavoidable to prevent cross contamination, and a singnificant part of the cleaning effect may be lost. As a large scale vacuum system of the Main Injector, it would be very difficult to keep cleanliness of surfaces after pre-treatments for a long time.

In situ bake out and glow discharge cleaning are widely used for accelerators and storage rings. In the case of *in situ* treatment, complicated surface pre-treatment procedures may be ignorable. In order to bake out the beam pipe, the magnet gap must be enlarged for using thermal insulations. This would increase the production and operation cost of magnets. Whereas *in situ* bake out can't be excluded from consideration, it would be applicable for some components with heavy outgassing rate such as injection and extraction elements or ion pump conditioning.

A benefit of the glow discharge cleaning is that it requires only standard vacuum equipments, in particular it can be done anytime and anywhere. Nevertheless, the *in situ* D.C. glow discharge cleaning needs more complicated distribution anodes in the beam pipe. *In situ* Electron Cyclotron Resonance (ECR) glow discharge cleaning, electrode-less glow discharge, is considered to be worth using for the Main Injector. It has an advantage of lower metallic sputtering because of the low plasma potentials. A microwave generator with a frequency of 1-3 GHz and a power capacity of about 500 w, and an additional magnetic field of 800-1 200 G are needed to the excitation volume. Fortunately, about 70% of 3.3 km circumference of the ring is inside magnets, the ECR glow discharge cleaning can be conveniently used for the Main Injector. It only requires an additional port on stubs of the beam pipe, placing a short monopole antenna which do not interfere with the beam aperture, but is capable of sustaining an uniform discharge through entire beam pipes.

6.3 Surface cleaning for the Main Injector

For the design and construction of the Main Injector vacuum system, a simplified procedure based on one used at a pressure of $\sim 10^{-9}$ Torr for accelerators and storage rings is given as follows:

1 Pre-treatment of beam pipes and vacuum components

1) Chemical cleaning with detergents in compliance with Fermilab specification.
2) Vacuum test.
3) Cover the openings with aluminium foils.
4) Store in plastic bags.

2 Conditioning the vacuum system in the tunnel

After a section installation is completed in the tunnel, its conditioning will be as follows:

1) Check leakage and tightness.
2) Bake out all pumps at 150°C, degas B-A gauges and RGA analyzers.
3) R.F. cavity, injection and extraction element conditioning.
4) ECR glow discharge cleaning for the beam pipes.

6.4 Clean vacuum

In order to protect a low outgassing rate of materials, it should be noted that to keep environmental and personal cleanliness is very important during assembly and installation. Bare hands can not be permitted to touch cleaned surfaces in normal operation. Tools and instruments placed inside the vacuum chamber should be cleaned in advance. Vacuum component cleaning and assembly should be in clean room conditions. Two main clean areas at least have to be set up. One will be vacuum laboratory for vacuum testing. The other will be a room which will be used exclusively for the assembly of vacuum components prior to their testing and tunnel installation.

6.5 Pack and store

Pack and store are common steps in all of above procedures. Once the component has been cleaned it may need to be stored before it can be assembled into a system and some thought must be given to packaging during this period. In general it is recommended that all openings be covered with new aluminium foil crimped into place, followed by prefabricated covers, and bagged in plastic. Whereas, the best way is to store cleaned vacuum components under vacuum as far as possible.

6.6 Venting

When the vacuum vessel is vented to atmospheric pressure for a short period of time, it is advisable to use nitrogen with ultra high purity to minimize the moisture adsorption on the surfaces of the vacuum system. It is very important to minimize pump-down time. Venting should always be on the chamber side, never vent the system from the foreline of the mechanical pump.

7 Reuse of VacIon sputter ion pumps

7.1 Introduction

Since the beam pipe is strongly conductance limited, small ion pumps with a nominal pumping speed of 30 l/s will suffice for the vacuum requirement of the new machine. Nevertheless, after a long time running, the pumping characteristics might have changed. The ion pump have to be appraised in order to ensure a long time running for the new machine.

7.2 Normal procedure of reusing ion pumps

1. Disassemble the ion pump from the Main Ring.
2. Remove the pump out of the tunnel;
3. Inspect the interior to make sure that it is free oil films, loose flakes, or heavy deposits and that the cathode plates are not excessively etched.
4. Check and clean the feedthrough, connector and cable.
5. Evacuate the pump immediately. Store the pump under vacuum. The pump can't be exposed to air for a long time.
6. Assemble the ion pump on a dipole or quadrupole magnet beam pipe assembly with an additional turbo-molecular pumping system for the glow discharge cleaning.
7. Detect leak; The total allowable leak rate should be less than 1×10^{-9} Torr l/s.
8. Glow discharge clean the beam pipe with an accumulated dose of 10^{18} ions/cm^2.
9. In order to minimize the pump-down time, the pump can be baked out at 200°C.
10. Vacuum performance tests for the ion pump and the beam pipe are linked and should enable a pressure of 3×10^{-9} Torr to be obtained in the beam pipe.
11. Fill up with high pure nitrogen previously, when the system needs to expose to air.

7.3 Vacuum test for the ion pump

Knowledge of the pumping performance is necessary to determine whether the pump is indeed functioning as described by the manufacturer and to provide more information for the new project. In order to understand the vacuum behavior of the new system, it is suggested that the pumping characteristics of the 30 l/s VacIon pump should be determined for only a few of selected samples. The results will be very useful for evaluation of the new system.

1. Apparatus for measuring pumping characteristics

In a molecular flow region, the pressure is a function of the geometry of the metering dome and the location of the inlet gas line. The standard may keep the pumping characteristics of measured ion pumps for same condition and same method. In order to measure the volumetric pumping speed of a high vacuum pump at pressures lower than 10^{-6} Torr, the test dome according to PNEUROP (European association of manufacture) or German Standard DIN28429 is recommended. The pumping speed measurement results from a gas flow obtained from the pressure drop across an orifice of known dimentions.

$$S = C(\frac{P_1}{P_2} - 1)$$

where P_1 and P_2 are the pressures recorded in the top and bottom of the test dome respectively. The conductance of the orifice is given as follows:

$$C = 91000\frac{d^2}{1 + \frac{e}{d}}$$

where d and e are the diameter and thickness of the orifice in meters.

2. Measuring procedure

1) Pre-evacuation with rough pumping to below the starting pressure.

2) Bake out the ion pump up to 250°C for 4 hours.
3) Stop roughing pump.
4) Start the pump, continuing to bake out for further 10 hours.
5) Degass B-A gauges.
6) Measure ultimate pressure at room temperature between 15 to 25°C after finishing bake out 48 hour.
7) Fill ultra high pure nitrogen of $3\times10^{-2}\cdot$S Torr l to make the pump saturated. The maximum saturated pumping speed is defined as the nominal pumping speed.
8) Measure pumping speed for nitrogen.

7.4 Possible upgrade

The lifetime of an ion pump is a function of the time necessary to sputter through the cathodes. A typical value for the VacIon 30 l/s sputter ion pump is 35 000 h at 10^{-6} Torr. The lifetime of pumps may be shorter due to shorting of the electrodes by loose flakes of titanium. It is supposed that, after a long time running at higher pressure on the Main Ring, the cathode plates of the pump should be replaced in order to ensure at least 10 year working for the Main Injector.

It is necessary to consult with the manufacturer about the rebuild of ion pumps. A new and unique cathode design, known as StarCell, recently developed by Varian to further increase the performance with noble gases may be selected to rebuild the pump. Comparative tests have shown that this cathode design allows hydrogen pumping at a pressure of 1×10^{-6} mbar for 8×10^{4} hours. Instability for noble gases is virtually avoided after pumping large amount of argon, thanks to a more uniform distribution of the fraction of argon pumped at the cathode.

8 Rough pumping units

Rough pumping units will be used not only for initial pump down, but also for leak tests. It may provide an additional ultra high vacuum pumping of the pressure of $\sim 10^{-9}$ Torr when needed. In order to obtain a better ultimate pressure of hydrogen, which is a major gas composition in the residual gases, an arrangement of two turbo-molecular pumps in series is considered because the hydrogen compression ratio of the turbo-molecular pump is very low. It is suggested that a rough pumping unit consist of an 100 l/s and a 40 l/s turbo-molecular pump backed with an 8 l/s mechanical pump. With the rough pumping unit spacing about 100 m, it is estimated that a pressure of $\sim 10^{-3}$ Torr will be obtained about 3 hours pumping. Also a pressure of $\sim 10^{-5}$ Torr will be achieved in about 20 hours pumping. At this pressure sputter ion pumps may be ignited.

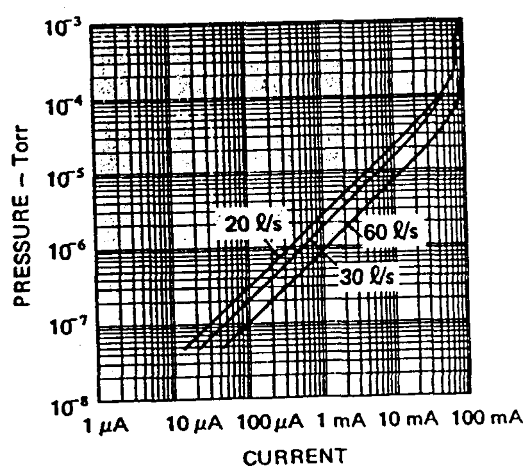
A small chamber will be locked to the rough pumping unit by a rubber sealed gate valve, and connected to the ring beam pipe by a corner metal sealed valve. The chamber also will house a mass spectrometer, a calibration leak, vacuum gauges and a small metal sealed venting valve. The pump-down will be done by turbo-molecular pumps with a liquid nitrogen trap, keeping the ring vacuum chamber absolutely free of hydrocarbon contamination. A manual valve between the turbo-molecular and mechanical pump will be used for connecting to a leak detector. Because of the high radiation level and neutron flux density during the operation of the machine, the rough pumping units are designed as movable components. Normally all units will be removed out of the tunnel before running the machine.

9 Vacuum measurements

9.1 Introduction

Vacuum measurements on the Main Ring are done by current readouts from ion pumps based on the Penning discharge. However, the VacIon pump can't be used for measuring a pressure less than 1×10^{-7} Torr. Fig.3 shows the pressure vs current characteristics from the catalog. Below pressure of 10^{-8} Torr, the parasitic currents in sputter ion pumps or in their power circuits are frequently comparatable to the currents drawn by the discharge in the pump, and the current in the power circuits can therefore hardly be relied on for pressure measurements. Therefore, a vacuum measuring system including total pressure and partial pressure instruments should be set up for the new machine.

Fig.3 Pressure vs current of the ion pump



9.2 Total pressure measurement

The total pressure measurement facilities, consisting of three different types of the gauge, are used to cover a wide dynamic range of a pressure from atmosphere to 10^{-12} Torr.

1. Pirani

The Pirani gauge is chosen in preference to thermocouple gauges for low vacuum measurement. For example, the range from atmospheric pressure down to 5×10^{-4} Torr is covered by a Pirani gauge of the Balzers TRO 015 type. Whereas the thermocouple gauge becomes unreliable above about 2-3 Torr. The extension of the range of this gauge to atmospheric pressure is very useful, especially during pump-down in a big system, although no precise vacuum measurements are required in this range. An indication that the pressure falls continuously is sufficient to show that the rough pumping work well.

2. Penning gauge

The Penning gauge is being considered, since it would appear to have some significant advantages. It is robust, and requires only a simple and hence relatively cheap power supply. The Balzers IKR 020, covered from 10^{-3} to $^{-9}$ Torr, is recommended as a main measuring instrument on the Main Injector.

However, the indication of the Penning gauge is always instable after a long time running. As D.Trbojevic's test on the Main Ring showed, pressure readings obtained from ion pumps were quite different from indications of B-A gauges. The actual pressure in the beam pipe might be one order of magnitude higher than the current readout of ion pumps. [4] It is supposed that oil backstream from forevacuum mechanical pump is usually unavoidable, thin oil films are formed on electrodes frequently resulting in reducing the

[4]Dajian Trbojevic,Nicholas Pastore,Measurement of the gas pressue and the residual gas composition in the Main Ring, Fermilab TM-1565,Feb.14,1989

discharge current in Penning gauges or ion pumps.

3. B-A gauge

For good operation, accurate information on pressure around the ring should be available. An advantage of using commercial B-A gauges with a measuring limit of 10^{-12} Torr and accuracy of $\pm$ 15% to measure pressure rather than using ion pump currents has been amply demonstrated. It gives relatively accurate pressure readout in the system. The B-A gauge will be used only for accurate vacuum measurement occasionally, or at very low pressures on the system. The hot filament of the B-A gauge should be required to last more than one year continueously in order to insure a long maintenance interval.

9.3 Partial pressure measurement–Residual Gas Analyzer

A residual gas analyzer (RGA) used for partial pressure measurement of the vacuum system *in situ* without interrupting operations unnecessary, has proved invaluable. For instance, it is used primarily to determine air leaks, solvent contamination, water vapor loading, etc. Because of its simplicity from the operational point of view, a radio frequency quadrupole mass spectrometer can be chosen for the new machine. A number of gas analyzer heads which will be placed around the ring and permanently connected to the central computer control system, will be used for obtaining information as to the dynamic behavior of the vacuum system under operating conditions and monitor the composition of the residual gas especially in case of vacuum failure.

9.4 Installation

A measurement array consisting of three different types of the gauge, will be mounted roughly in the middle of each section with a ConFlat flange. A Pirani and a Penning will be powered by a combined control unit which derives interlock operations. The sector in straight sections will be usually equipped with additional gauges.

For economy, most of these gauges will not be permanently cabled apart from those which in the R.F. sections and some measuring zones. The rest will only be used with local portable control units for vacuum commissioning or leak detection.

The gauges should be mounted on stubs of the beam pipe in such a way that no part of electrodes will be within line of sight. In this way the gauges will be less disturbed by charged particles and low energy radiation resulting from the interaction between the beam and the residual gas. It will be also important to prevent electrons from the gauge filaments being drawn into the positive charge of the beam.

9.5 Calibration

Because the pressure is measured indirectly, the Penning gauge and B-A gauge need to be calibrated before being mounted. It is necessary to construct a calibration system to obtain the pressure values at which secondary gauges will be calibrated in comparison with a reference gauge. It should be checked mostly in metrological laboratories, such as NIST (formerly NBS) in the United States prior to calibration. In addition, a Spinning rotor gauge with high accuracy is possibly used as a reference gauge.

10 Vacuum seals

The seals required on the vacuum system of the Main Injector will be mixed. In general, all metal seals including the: ConFlat, Wheeler, Foil, Wire, C-ring, Diamond and Hélicoflex may be used. The following kinds of the seal will be needed for the Main Injector.

1. ConFlat seal

ConFlat seals developed by Varian are used in the vacuum system as a standard connection with a compatibility to all conventional vacuum equipments such as VacIon pumps, valves and gauges. The sealing edges are designed to bite 0.3 to 0.4 mm on each side of 1.6 to 2 mm thick gaskets made of annealed OFHC. Sealing force required is about 350 kgf/cm. It can be baked out to 450 °C. ConFlat seals may be reused using the same gasket, by increasing the pressure slightly with each seal. The manufacturing limitation is about 300 mm in diameter.

2. Aluminum 'diamond' seal

Quick disconnect flange couplings with a 90° diamond shaped gasket developed by CERN/Heraeus are already chosen for most of vacuum connections of the Main Injector. It is made of pure aluminium or creep-resistant alloy, requiring low sealing force of about 50 kgf/cm. It may withstand the roughest handling, and which is the least sensitive to the application of a non-uniform pressure over the seal periphery and give a reliable ultra high vacuum tightness. The flat flanges compared with ConFlat are easy to manufacture, especially for non-circular seals. The seal has a disadvantage of being non-reusable, however, in view of their low cost this is not considered a serious problem.

3. Hélicoflex seal

Hélicoflex seals developed by French Atomic Research Center and Le Carbone Lorraine-Cefilac Etanchéité, is a flexible metal O-ring with an elastic core which supplies the sealing force. The materials of the sealing lining currently used are aluminium, indium, silver and copper. In actual fact, these flanges were initially designed by PNEUROP dealing with vacuum technology. Their recommendations were based upon the use of elastomer O-rings which require a very low compression load. The sealing force of the flanges is about from 140 to 215 kgf/cm. Such a system can withstand many 200°C bakes out and repeated opening and closing without leaking. It is best to be used for the more frequently opened joints. Although Hélicoflex seals are more expensive, many accelerators are already showing great interest in such products.

4. Vatring

It is used for all-metal gate valves developed by VAT. The conically arranged sealing partners are made of stainless steel which are only elastically deformed. The Vatring has a very large cycle life of 10 000 cycles before first service, and can be baked out to 450°C in the open or closed position. A RF all metal gate valve providing with reproduceable RF contact due to load springs will be appropriate for the beam pipe with low RF resistance.

11 Leak detection

11.1 Introduction

Making a vacuum vessel leak tight is very important in a ultra high vacuum system. Although the leak testing is a time consuming and laborious work, 100% of elements, devices and purchased vacuum products should go through extensive acceptance leak test, and all assemblies should undergo a complete leak test to ensure that none is mounted on the vacuum system without having its main characteristics checked.

11.2 Leak detector

With presently available commercial products, the helium mass spectrometer leak detector, sensitivity is in the order of $\leq 10^{-11}$ Torr l/s, has been universally accepted for sensitive leak detection of vacuum components and systems. The minimum detectable leak rate on a vacuum system depends on the sensitivity of the instrument, the background tracer gas, and the speed of the pumps attached to the chamber, etc. All of these parameters can be optimized to increase leak detection sensitivity. The leak detector should be connected at the point between the turbo-molecular pump and the mechanical pump. The leak detector has to be equipped with a liquid nitrogen cold trap to protect the beam pipe and mass spectrometer from contamination from the oil diffusion pump, normally used in the leak detector.

11.3 Leak detection methods

Dynamic leak measurement methods of applying helium leak detector for the Main Injector are mainly as follows:

1. Measuring the total leak rate

The leak measurement gives the value of the total leak rate of the system being measured. For this purpose, the helium leak detector is connected into the forevacuum of the system being tested. The system to be leak tested is enclosed in a plastic hood into which helium is injected so that the system is surrounded by a mixture of air and helium. If there are leaks on the object, helium may penetrate into the system, the detector should measure the test gas concentration on the opposite side in the dynamic status. On a large system, the accelerator ring, the hood method can be applied to sections of the system by enclosing portions of the system in a smaller plastic bag, thus roughly localizing any leaks present.

2. Leak location

The total leak rate measurement can not help to locate a leak. The gas probe method is widely applied since it facilitates localizing the leak within a small area. A stream of helium is spread on the suspected area, and the gas penetrating into the system is pumped via the detector so as to indicate leak position.

3. Leak detection for the Main Injector ring in the tunnel

The detector should be attached to a rough pumping unit in the tunnel instead of directly connecting to beam pipes. This is the most sensitive method of leak detection–all of the helium probe gas that enters the leak is compressed into the backing line for the detector to sample. For large distances between the leak detector and leaks, the long time constant($\sim$10 seconds) makes leak detection difficult and time consuming. A lateral connection for leak detection about every 100 meters should be adequate. Leak detecting should be accomplished with rough pumping mechanical pump 'off'. The turbo-molecular pump is backed by the leak detector through a manual angle valve.

4. Leak detection with the residual gas analyzer

While rough pumping units are removed out of the tunnel, the residual gas analyzer will be conveniently used for leak detection on the ring.